# ADEGUAMENTO SISMICO REVERSIBILE DEL CAMPANILE DI SANTA LUCIA

# SEISMIC AND REVERSIBLE UPGRADE OF THE BELL TOWER OF SANTA LUCIA

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**SOMMARIO**

**L'adeguamento sismico di strutture di rilevanza storica e culturale richiede il rispetto di vincoli tesi a rendere la progettazione dell'intervento compatibile con la conservazione delle caratteristiche artistiche della costruzione. In questo spirito è auspicabile realizzare il miglioramento sismico senza alterare l'aspetto ed il meccanismo statico del sistema strutturale o, se questo non risulta posibile, rendendo reversibile l'intervento al fine di poterlo rimuovere nel caso di mutate necessità o di avanzamento tecnologico. Questa filosofia d'approccio è stata seguita nella progettazione dell'intervento di adeguamento sismico per la torre campanaria di Serra S. Quirico (Ancona). Un traliccio di tiranti in FRP è stato applicato alle pareti interne della struttura in muratura e ancorato alla base attraverso una pre-esistente soletta in cemento armato. In questo lavoro sono riassunti gli aspetti progettuali e costruttivi, nonché la analisi degli effetti benefici sulla capacità di spostamento, attraverso analisi statica non-lineare, del sistema rinforzato rispetto alla struttura nuda.**

**ABSTRACT**

**Seismic retrofitting of structures belonging to the architectural heritage requires meeting of constraints which are related to preservation of artistic features. Any developed intervention must do not change appearance, structural mechanism and must be also not invasive. These innovative principles, that are quite obvious from a cultural and artistic point of view, are very restrictive constraints to engineer's jobs but innovative materials, such as composites, may be helpful in the matter. This philosophy was applied to the design process of the retrofitting intervention for the bell tower of Serra S. Quirico (Ancona – Italy). A light FRP ties system have been gripped on the inner walls; this reinforcing**

**structure is anchored at the base on a formerly built reinforced concrete slab independent of the tower foundation. In the present paper design and installation processes are summarized. Comparison of non-linear static analyses of reinforced and un-reinforced structures is also presented.**

## INTRODUCTION

Right after Friuli (1976) and Irpinia-Basilicata (1980-1981) earthquakes a new technical regulation, dedicated to seismic retrofitting of building, was promulgated in Italy. It dealt with the idea of “working over to make the structure resistant to the seismic actions”. Those interventions, based on reinforced concrete and steel rebar, appeared extremely harmful for structures belonging to the architectural heritage. Construction steel, for example, was commonly used in the case of masonry structures; its volumetric expansion due to corrosion induced wide cracking in retrofitted elements. After recognizing damages of those “seismic upgrading” following the regulations, members of National Committee for Cultural Heritage Seismic Risk Prevention claimed the principle of *seismic improvement*, instead of seismic adjustment, by techniques respecting the structural system and preserving their integrity. This way of thinking have been clearly claimed by 1.16.1996 decree explaining the mandatory seismic improvement for historically-artistically relevant structures as “interventions on the structural elements of the building in order to increase the safety margin without changing the main features of global behaviour”.

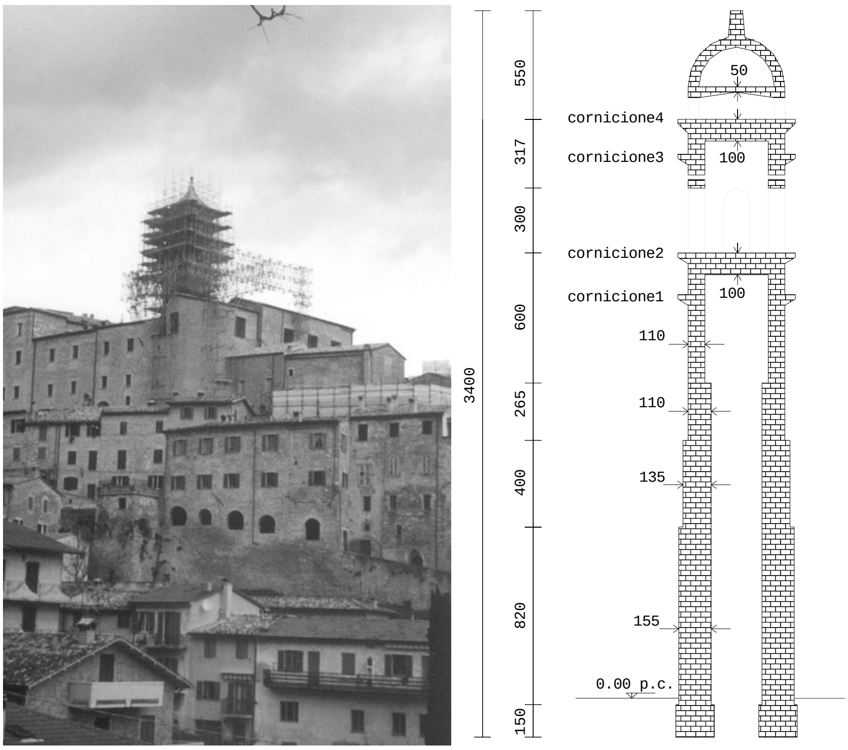


**Figure 1. The bell tower in Serra S. Quirico (AN) and its structural section.**

It’s worth noting that is not possible to get completely removable interventions keeping their structural effectiveness; this is why the listed principles are should be called *asymptotic* concepts. Innovative structural materials are helpful in the matter. Varying composites matrices quantities, fibres types and relative percentage, several structural problems can be addressed; it opens new scenarios for engineers. Industrial processing and economical reasons only, limit these new structural capabilities. Continuous fibres composites, due to their lightness, strength and durability features, are particularly powerful. The intervention described in the following shows it. The focused structure is an aging bell tower affected by the Umbria-Marche earthquake (1997). The S. Lucia's church bell tower is a sac-masonry structure built during the XV century. It is a tall structure (approx. 32 m; 1200 tons in weight) at the centre of the little town of Serra S. Quirico that is a mid-age suburb near Ancona (see Figure 1). To improve the structural seismic strength, inner steel beams reticular system anchored to the masonry was formerly designed. It was conceived to be a fully substitutive structure in case of earthquake. It would need the removal of existing wooden floors and their replacement by steel panels and anchoring of steel profiles in the original masonry. As the designed intervention strongly breaks the concepts of structural restoration cultural heritage department decision authorities rejected this proposal judging it too much invasive. Then, the former supervisor to the architectural heritage of Marche, Arch. Enrico Guglielmo, asked for Professor Edoardo Cosenza consulting for a "light" solution by innovative materials. The whole process, from design to installation of composites, took few months, finishing in the summer of 2002. Detailed structural analysis preceded application of retrofitting to the structure. Refined 3D Finite Elements Model has been developed and dynamic structural identification by wind and vibration machine (vibrodine) excitation followed. Details about FEM analysis and on-site dynamic characterization are given in [1,2]. In the following the design process, the realization phases and the seismic analysis of the bell tower are described.

## RETROFITTING DESIGN AND INSTALLATION

Design process intended to get the targets of the principles listed above, being effective and as transparent as possible. A reticular system, made of horizontal and vertical carbon fibre, is anchored on the inner walls of the tower (see Figure 2). The FRP has been installed without removing the original wood beams at floors; wooden panels were temporarily removed and restored at the end of the whole process. Horizontal short composite elements were spaced in the walls corners to improve the grip. From the structural point of view FRP design aimed to greatly improve seismic capacity of the tower as discussed in the following sections. The realized intervention avoids local masonry failures and improves the seismic strength of the structure.
Usually structural engineering practice neglects masonry tension strength, while FRP ensure a monolithic behaviour for high intensity earthquakes. The structure keeps its static mechanism for low intensity seismic activity because the added stiffness is very low in comparison to the one of the bell tower, but in case of strong motion the tension side of masonry goes loosing cohesion allowing the composites start working; then the masonry behave as reinforced structure. A reinforced concrete slab (70 cm thickness, 40 micro poles), built as foundation for formerly proposed steel structure, was used for anchoring composites to the ground without overloading the original tower's foundation. The composites used were made of. 20 cm wide double layer fabric, 600 gr/mq in weight and 0.67 mm in thickness. A key aspect of the intervention was the composites-masonry grip system, the fabrication details and the anchoring of the composites to the foundations. All those problems were managed by the expertise of professor Alberto Balsamo.

The composites installation strictly followed design specifications. Even though the small available space and the presence of the wood beams, the composite textile allowed a simple intervention installation. To obtain a good grip masonry samples were analysed to get the optimum surface treatment. In Figure 3 aspects are highlighted. Anchoring steel plate detail is shown, also the horizontal and oblique elements are displayed close to an original wooden beam. Anchoring plates are very stiff since it should not be the weakest element of the whole system. The focused plate is in the most irregular corner of the inner part of the bell tower, and then a large quantity of filling resin was needed. Horizontal elements improve FRP grip on masonry. The composite structural system geometry was locally modified to do not pass over the tower openings.

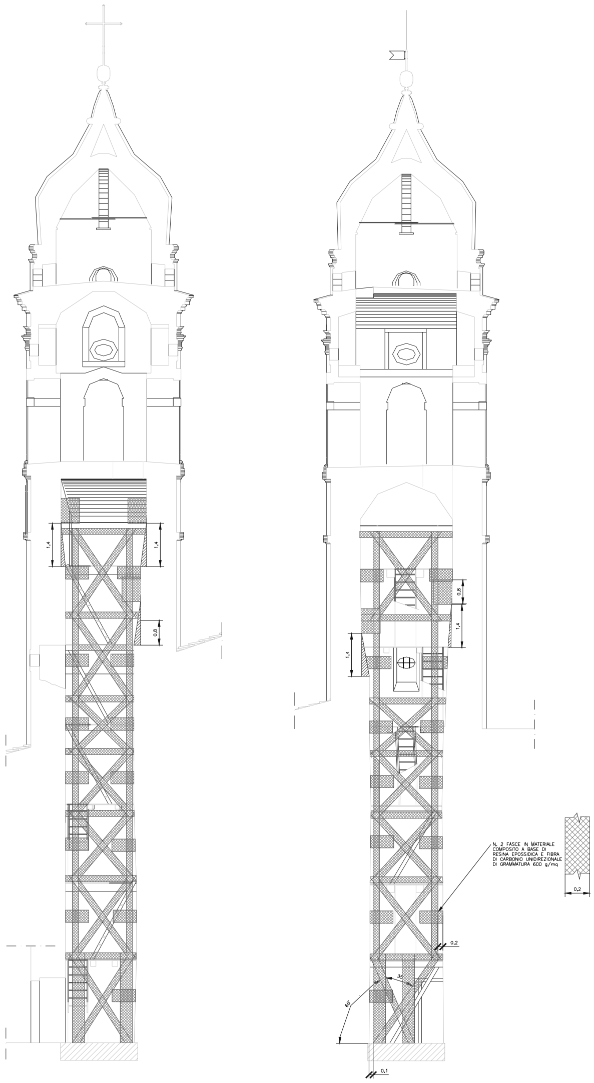


**Figure 2. Bell tower composites intervention relief into two sections.**

The lack of pictures brightness in the pictures is due to the achievement of the “transparency” target of the intervention design process: the improvement of structural strength is strong but the installation is “light”.

It is worth noting that the intervention is to be considered as “reversible”: the applied FRP can be removed by heating [3]. In a lab test composite material has been heated by air furnace and temperatures of composite and underlying brick (11 cm thick) are monitored. At air temperature of about 300°C resin started melting (temperature of the resin of about 90°C) and composite was removed by hand**.** The brick temperature was about the same of the surrounding environment meaning that thermal inertia of the masonry is sufficient to preserve art work which may be on the other side of the intervention.

**Figure 3. Installed composites and base anchorage. Composites near to un-removed wooden floor. Intervention anchoring details.**

## RETROFITTING EFFECTS ANALYSIS

In the following non-linear seismic analysis of the structure is described. Push-over analysis has been developed conservatively considering ineffective the constraint given by the church to the bell tower in the case of rare seismic event; the structure is therefore isolated in respect of other buildings.
Moment-Curvature diagrams have been computed for both reinforced and un-reinforced structure. Masonry stress-strain relationship has been modelled as in [4], considering Powell and Hogdinson constitutive law; FRP has been considered linear elastic.
Load-displacement curve is followed moment-curvature analysis by double integration. Horizontal loading pattern reproduces the first oscillation mode and it has been gradually increased until the collapse of the structure. Displacement monitored refers to centre of gravity of the tower.

Figure 4 compares retrofitted and un-retrofitted structure push-over curves. Crisis is conventionally assumed to happen when masonry deformation is 0.2% or FRP deformation is 0.5%.

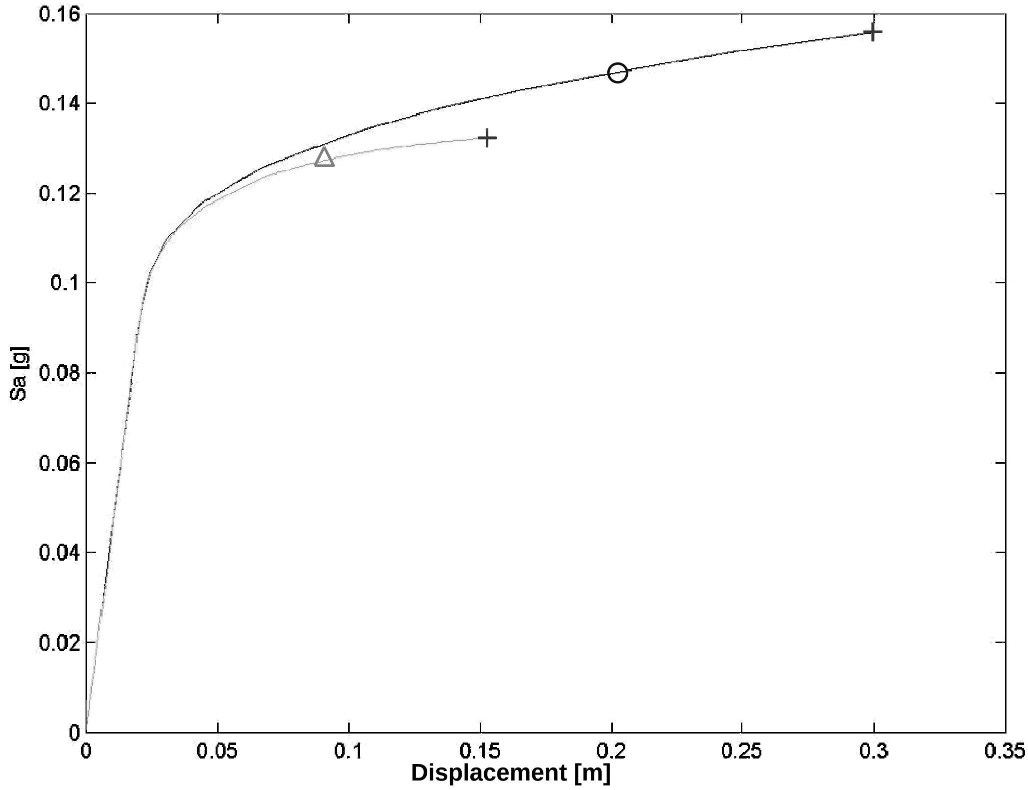


**Figure 4. Retrofitted and un-retrofitted push-over curve comparison. + Masonry deformation: 0.2%; ● FRP deformation: 0.5%; ▲Crisis due to bending-shear interaction**

For the structure as un-retrofitted interaction of bending and shear has to be taken into account; it may induce early collapse. The Mann & Müller model [5] has been considered to plot the bending-shear stresses interaction domain which is given in Figure 5.

In the retrofitted case at the collapse point the FRP reticular system transfers shear by horizontal belting, which behave as stirrups, and diagonal elements which are necessary to get equilibrium in no-bending conditions. Therefore in the compression masonry no significant shear tension is generated. This is, clearly, one of the main benefits of the intervention.

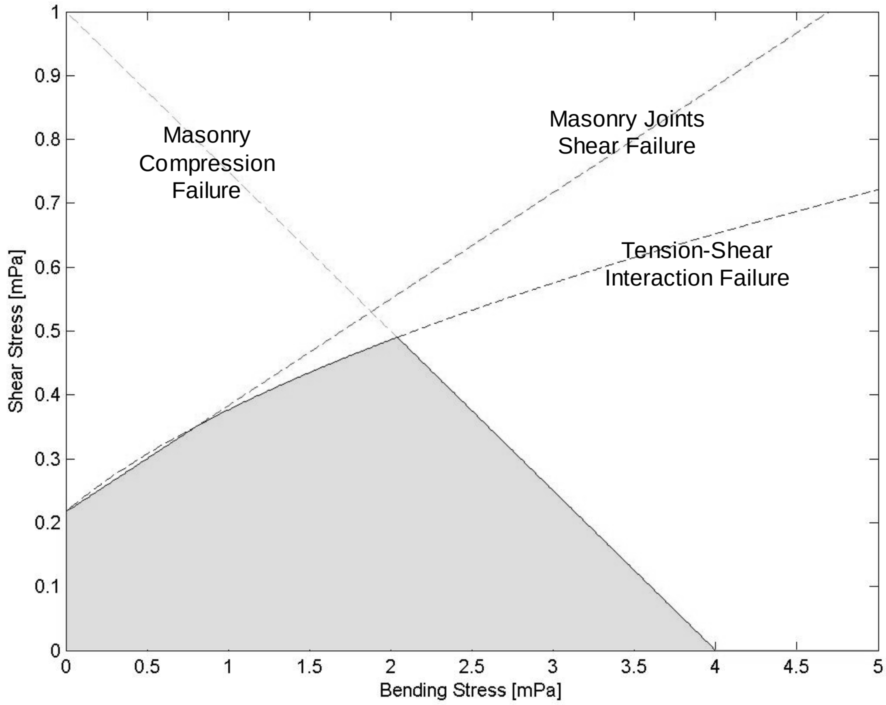


**Figure 5. Bending-Shear Interaction domain.**

From push-over analysis is possible to compare capacity to seismic demand using the capacity spectrum method [6].
Figure 6 gives:
Elastic spectrum in terms of acceleration (ordinates) and displacements (abscissas) according to Italian seismic code [7] for the seismic level of the Serra S. Quirico Area: PGA is 0.25 g amplified by a 1.25 coefficient taking into account soil conditions and by a 1.4 factor taking into account importance of the structure which is included in the residential part of the town and is right above the town-hall building.;
Constant 4.5 ductility spectra;
Push-over curve for un-retrofitted structure.
Un-reinforced capacity is lower than demand if the shear effect is considered. In the case of reinforced structure capacity largely exceeds demand; comparison is not given for sake of brevity.
From demand-capacity analysis is possible to accurately evaluate seismic risk of the structure by considering hazard curve at the site (Figure 7) where exceeding probabilities are given as ordinates for given PGA (abscissas). Hazard curve is computed for the ground motion attenuation relationship plus one standard deviation.
On the same plot limit states PGA's are given according to the seismic code for damage begins and collapse (0.15g-0.25g). Maximum sustainable accelerations for the reinforced and un-reinforced structure are also given.
Analysis confirmed hardly acceptable collapse probability for the un-reinforced structure while retrofitting elongates greatly the earthquake's return period associated to the crisis of the structure which is compatible with the monumental nature of the bell tower.
Results only reflect global behaviour of the structure. Several local interventions along the structure, and particularly at the top of it, avoid local collapse which is quite common in

this kind of structures. According to this principle traditional improvement of the masonry and steel chains have been applied to the bells room.

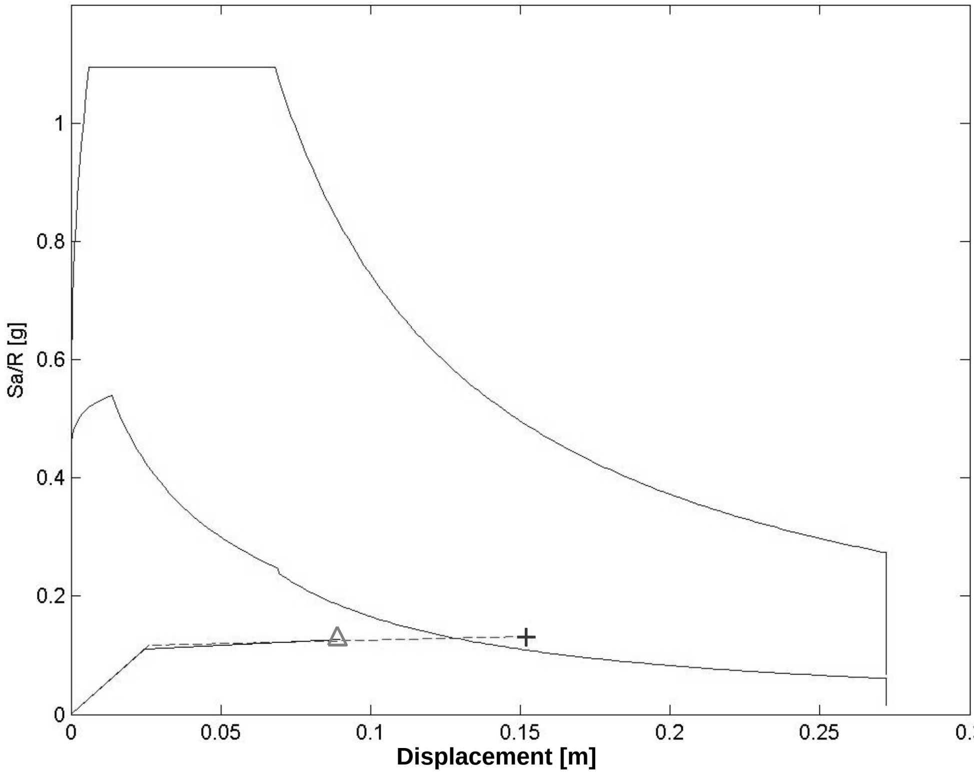


**Figure 6. Un-reinforced structure capacity spectrum.**

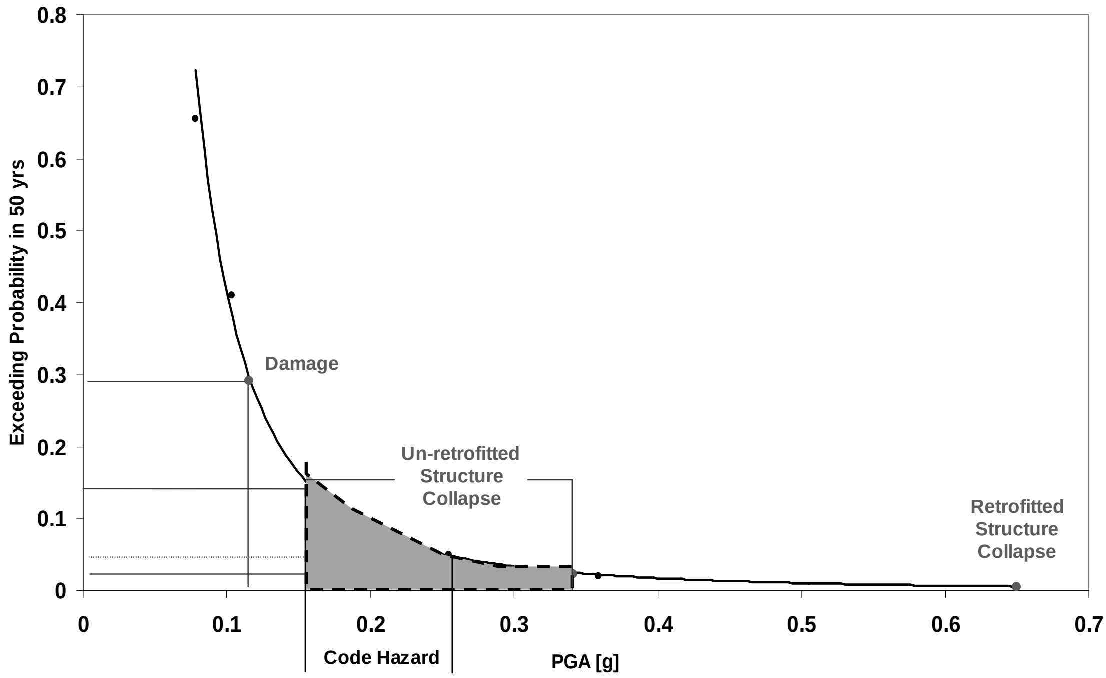


**Figure 7. Hazard curve for Serra S. Quirico (AN).**

## CONCLUSIONS

The intervention on the bell tower of the S. Lucia's church is an interesting application of composite materials in the structural restoration. Transparency and low impact target are fully achieved avoiding holes and removal of wooden beams and slabs. The composites are placed directly on the masonry surface so they are removable and almost invisible. In Figure 8 one can see the bell tower after retrofitting application; one can se no evidence of the intervention.

Non-linear seismic analysis shows how retrofitting decreases significantly failure probability if global reinforcement is accompanied by local interventions on masonry and chains in the upper part of the bell tower.

The application is a case of fruitful interaction among state offices; architects and engineers trough innovative structural techniques [8].

**Figure 8. Bell tower after intervention.**

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## REFERENCES

[1] T. Pelella, G. Mannara, E. Cosenza, I. Iervolino, L. Lecce, 2001. Structural dynamic investigations on the bell tower from the S.Lucia's church – Serra S. Quirico, Ancona, 7th Int. Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures, Assisi, Italy, October 2-5.

[2] E. Cosenza, I. Iervolino, E. Guglielmo, 2003. Seismic Performance Improvement of the Bell Tower in Serra S. Quirico by Composites, FRPRCS-6 Int. Symposium , Singapore.

[3] E. Guglielmo, E. Cosenza, 2003. Un esempio di miglioramento sismico reversibile: il caso del campanile della chiesa di S. Lucia, Serra San Quirico – Marche, Atti del XIX Convegno Internazionale Scienza e beni Culturali; La reversibilità nel restauro: riflessioni, esperienze, percorsi di ricerca., Bressanone, 1-4 luglio 2003.

[4] G. Faella, G. Manfredi; R. Realfonzo, 1993. Stress-strain relationships for tuff-masonry: experimental results and analytical formulations, Masonry International, vol. 7, n.2, pp 35-61.

[5] W. Mann, H. Müller, 1982. Failure of shear-stressed masonry - An enlarged theory, tests and application to shear walls, Proceedings of the British Ceramical Society, Vol. 30, pp. 223-235.

[6] P. Fajfar, 1999. Capacity spectrum method based on inelastic demand spectra, Earthquake Engineering & Structural Dynamics. Volume 28, Issue 9, pp. 979-999.

[7] Ordinanza n. 3274, 2003. Presidenza del Consiglio dei Ministri, "Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e normative tecniche per le costruzioni in zona sismica", supplemento ordinario 72 alla Gazzetta Ufficiale n° 105.

[8] E. Cosenza, G. Fabbrocino, 2003. Tecnologie e materiali innovativi per la salvaguardia dei beni architettonici, storici ed archeologici, Recupero e Conservazione, n. 52, pp. 92-97.